TCTM: an evaluation framework for architecture design on wireless sensor networks

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Abstract: This paper presents an evaluation framework for architecture designs on wireless sensor networks (WSNs). We introduce a simple evaluation model: triangular constraint tradeoffs model (TCTM) to grasp the essence of the architecture design consideration under transient wireless media characteristic and stringent limitation on energy and computing resource of WSNs. Based on this evaluation framework, we investigate the existing architectures proposed in literature from three main competing constraint aspects, namely generality, cost, and performance. Two important concepts: performance efficiency and deployment efficiency are identified and distinguished in overall architecture efficiency. With this powerful abstract and simple model, we describe the motivations of major body of WSNs architectures proposed in current literature. We also analyse the fundamental advantage and limitations of each class of architectures from TCTM perspective. We foresee the influence of evolving technology to futuristic architecture design. We believe our efforts will serve as a reference to orient researchers and system designers in this area.

Keywords: performance; evaluation; modelling; generality; cost; constraint; wireless; efficiency.


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1 Introduction

There is a wealth of architectures in the literature for Wireless Sensor Networks (WSN) applications, but there is no dominant one like internet architecture. The key to success with this architecture is the modularised design, where the design of each protocol layer is decoupled from other layers. This enables the rapid development of internet protocols, which have been designed and implemented by independent entities. The use of standardised interfaces between layers has enabled compatibility between these independently designed protocol layers. However, in WSNs, standard TCP/IP is infeasible due to the unique characteristics of WSNs. From kickoff of WSNs, energy budget and computing resources are severely constrained owing to the limited physical size of the nodes. Hence, protocol stacks that have large memory footprints and complex algorithms are not desirable. In addition, the broadcast and non-deterministic nature of the wireless channel creates interdependencies between each layer, especially with the low-power communication techniques. Therefore, stringent layering without interfaces between nonadjacent layers will not work efficiently in wireless networks as wired networks do. Recent empirical studies motivate that the properties of low-power radio transceivers and the wireless channel conditions should be considered in protocol design. Finally, the event-centric approach of WSNs requires application-aware communication protocols.

When we come to evaluate the proposed architectures in WSNs literature, we realise that over the last few years of WSNs evolvement, a large number of architecture solutions have been introduced according to de facto application specific methodology, respectively targeted wide range of applications such as environmental tracking applications, medical and industrial applications, home automation applications, surveillance systems, etc. This diversity requires a specific design methodology and specific settings in the architecture for the targeted application. If we consider all of the specific scenarios and different metrics in the architecture evaluation, it will be difficult to compare with each other (Yu, 2013). We cannot see the big picture as we immerse ourselves totally into complicated details. Nevertheless, a system can be considered at various abstraction levels, allowing to consider only relevant properties and behaviours at different abstraction levels, whose relevancy will depend on the context (Yu et al., 2011). In this paper, we will introduce an evaluation methodology from high-level abstraction, concerning only profound pros and cons from viewpoints of tradeoffs between generality, performance and cost in architecture design.

The rest of the paper is organised as follows. In Section 2, we will further analyse the status and challenge of current WSN architecture evaluation practice. We emphasise that while individual evaluation work is effective in its own term, for the purpose of widespread application of these architecture solutions as industry required, it is not valid yet. Based on this observation, in Section 3, we define the purpose of our evaluation framework is to provide high-level abstract information regarding architecture inherent performance pros and cons. Then we put forward our distinctive insight on triangle constraints in general system architecture evaluation based on three main competing metrics, namely QoS performance, cost and generality potential. We further show how the evaluation model guides the performance evaluation in a balanced way of combining development efficiency and performance efficiency in the context of system development life cycle (SDLC). In Section 4, we showcase possible new classification and evaluation of WSNs performance from TCTM perspective. In Section 5, we illustrate how evolving enabling technologies impact on performance evaluation. TCTM model is flexible and open to alleviate the impact. Conclusion is made in Section 6.

2 Application specific design as a challenge in system evaluation

Application specific design focuses on performance of each individual application while sacrificing generality. Still referring to layered structure, the distribution of the functionality in each layer depends on the preference of individual designers on specific application circumstances. Standard interfaces between layers like TCP/IP are no longer available. While this methodology has proved its capability to provide light weight performance gain for individual application, various problems have emerged as critical challenge for industry and academia from implementation perspective (Yu et al., 2013) as listed below.

- Generality is lost with performance focus. Generality are realised through abstractions to cover a variety of different protocols under the same layer, and
abstractions will cost computing resources and hinder the performance. We have to choose performance when trading between performance and generality in WSNs context.

- Research community so far provided a wealth of innovative solutions, and each solution has its own assumptions about the other layers. Therefore integration and reusability are challenging.
- Moreover the protocols are evaluated in ad hoc manner by respective authors. Their evaluation processes are not reproducible in most cases. True contribution and alternative solution comparison are partially based on metrics selection favourable to their own solution. As a final product, factors influencing the performance are huge in design space (Yu, 2013).

In the literature, various sensor network architectures (Madani et al., 2007; Prasad, 2008; Kawadia and Kumar, 2005; Dunkels et al., 2007; Buonadonna et al., 2001; De Poorter et al., 2011; Troubleyn et al., 2008; Mahlknecht et al., 2005; Huang et al., 2006; Li and Znati, 2006; Chen et al., 2009; Kawai et al., 2009; Zink et al., 2010; Mishra et al., 2011; Lindsey and Raghavendra, 2002; Heinzelman et al., 2000) have flourished in the past ten years. Most of the evaluation work are solid and sound in claiming better performance than related previous work under specified spectrum of conditions and assumptions. Interestingly, there is few work concerning the wholeness of the concept of performance as final product in WSN context. Without fully understanding the dynamics of performance and what elements constitute the performance, performance evaluation is partial and prejudicial. It is difficult for industry practitioners to lay judgement about true strength and weakness of the proposed algorithm and to answer questions like such: “What about performance metrics other than claimed better performed metrics? What will happen in the fluctuant real world without strict satisfaction of these assumptions? What is the cost to develop and maintain the prospective architecture from industry economic perspective?”. Without a high-level abstract framework as a consensus to guide the researcher’s evaluation practice, individual simulation and comparison of low-level selective performance metrics, no matter how realistic they are, will not help much in answering afore mentioned questions. We will tackle the evaluation problem in this regard.

3 Triangular constraints tradeoffs model (TCTM)

3.1 System architecture evaluation fundamental concepts

System architecture is the conceptual model that defines the system structure, externally visible properties of components, and internal interaction among them. Architecture design is a process that defines and refines components based on reasoning about the goal and structure of the system. An architecture evaluation framework provides a comparison platform for different architectures. A system can be evaluated through different viewpoints corresponding to different aspects of concerns of systems. Moreover, evaluation framework should be a dynamic evolution process as new science and technology advances would make certain constraints relax and push new frontier challenges.

Since any evaluation framework can only provide one view of the possible perspectives that focus on certain metrics, it is important that one should first focus on

- clarifying the purpose of the evaluation
- developing key evaluation questions or metrics accordingly.

The purpose of our evaluation framework is to

- provide high-level abstract information regarding architecture inherent performance pros and cons based on three main competing metrics
- demonstrate the contribution of the evaluated architecture towards broader goals.

3.2 Triangle constraints in general system architecture evaluation

Traditionally the Project Constraint Model recognised three key constraints; ‘Cost’, ‘Time’ and ‘Scope’, and these are also referred to as the ‘Project Management Triangle’ or ‘Iron Triangle’, where each side represents a constraint. One side of the triangle cannot be changed without affecting the others. It is useful to help with intentionally choosing system biases according to the goals of the project.

Figure 1 Triangular constraints (see online version for colours)

Inspired by Project Constraint Model, when we investigate WSNs architecture design and evaluation, we observe corresponding ‘Iron Triangle’ in the architecture evaluation modelling consisting of three key constraints, namely performance gain, generality and resource cost. These constraint metrics cannot be optimised perfectly simultaneously. In another word, optimum optimisation of one metric from the triple constraints cannot be achieved without the penalties from the others. The shift of focus for
the three constraints can capture the main characteristic of the architecture behaviour.

**Resources cost:** Energy and computing resources (CPU and memory) limitation is the primary concerns when WSNs just started due to the cubic centimetre level form of the nodes. Basically battery is irreplaceable in the fields if we consider the harsh environment, amount of nodes and the human resource cost of the replacing work. Energy consumption mainly involves signal transmitting/receiving and CPU computing, and it is estimated that the energy consumption when transmitting 1 bit of data on the wireless channel is similar to energy required to execute thousands of cycles of CPU instructions (Yick et al., 2008). The implication for this phenomenon is that node processing is far more energy efficient than only signal relay. Nevertheless, CPU and memory limited capacity indicates that WSNs cannot bear the luxury of any complex and advanced algorithm. Without battery (supply), antenna technology (consumption) and IC technology (computation) big breakthrough, resource cost will remain critical in architecture design and evaluation.

**Performance:** Performance is the primary goal of any application. As high-level abstraction, here performance is a collective word covering diverse Quality of Service (QoS) metrics. As applications evolve, more advanced requirements to underlying architecture are emerging. Under current resource cost restriction, for the purpose of optimal performance, WSNs system designers adopt a practical methodology: application specific design. To realise the required performance of WSN, many research groups have utilised every means to make their work done. Roughly, they tried to follow the TCP/IP reference model, but applications were in general vertical integrated by their own set of components that are specifically designed to work together in this very application. Performance is gained by the cost of generality and component reuse.

**Generality:** Generality requirement for WSNs architecture designers is an extra metrics in addition to resource cost and performance gain from historical view of the WSNs development. It is secondary for designers to consider in individual designing practice. However, for widespread application and commercialisation purpose, generality is critical as much as the other two metrics. We can draw lessons from the success of internet. Internet backbone TCP/IP is successful in its modularity instead of previous monolithic solution, such that applications need not be built form bottom up: from hardware, hardware drivers to application functionality. Different innovations in layering module can fit in the layers that they reside in with assumption of the lower layers support and higher layers compatibility. Modularity facilitates the innovation by individual efforts that can be conveniently adopted by existing architecture. Separation of concerns is crucial to the design of the layering architecture in which great efforts have been made to separate concerns into well-defined layers. This allows protocol designers to focus on the concerns in one layer, and ignore other layers. The cost of generality is inefficiency: from application raw data (the meaningful payload) each layer’ header is attached to original raw data from top layer all the way down to the physical layer signal bits ready for the transmitting. Notice that the fundamental purpose of the transmission is the part of the application raw data, whereas the information sent with it, such as headers or metadata, is solely regarded as overhead to facilitate delivery. In WSNs context, this overhead has significant impact on overall energy consumption and further network lifetime. However, Header encapsulation is essential for designing modular communication protocols in which logically separate functions in the network are abstracted from their underlying structures.

We summarise that the aforementioned three metrics deeply intertwine in such a way as Figure 2. The cost of the layering and generality is more layers of

- encapsulation
- abstraction
- modularisation

to contain differences of coexisting protocols in the same layer, so the performance efficiency of the overall network stack will drop considerably due to more layers of wrapping and unwrapping around original raw data.

Resource cost on the other hand increases when dealing with transmitting and receiving of more overhead signal bits from antenna. When we try to reduce resources cost as a single purpose, as in literature energy efficiency surveys indicated, there is various means that to reduce transmitting power and memory footprint to the lower limit at same time maintaining basic operation. In this case, performance and generality are too luxury to expect. Lower transmitting power means less signal coverage and more interferences.
noise; and lower memory footprint means complex algorithms like nonlinear programming, evolutionary multiobjective optimisation are infeasible. Even routine algorithms need more skilful programmers to develop. In such a simple basic settings, generality is out of the question.

The third spectrum of the constraint triangle is performance gain. Industry experiences show that performance and generality are natural enemies under energy resource constraint. That is why application specific methodology prevails over other methodologies in WSNs designs field. Whatever means which are suitable can be used in an ad hoc way to optimise performance for one specific application. The different effect of generality focused design and application specific design is analogous to the difference between general practitioner and specialist. The specialists emphasise expertise in depth of specific area while general practitioners emphasise the width of the involved area.

3.3 Triangle constraints tradeoffs reduce to two architecture efficiency tradeoffs

We further elaborate the triangular constraints tradeoffs as presented in Figure 3. Let us first extract and distinguish two important concepts for architecture evaluation from Figure 3.

Due to the inherent constraints of sensor nodes, resource efficiency is one of the key requirements and critical focus of WSN research. When respectively combining generality and performance to resource cost consideration, two important types of efficiency are identified: Network QoS performance efficiency (PE) and deployment efficiency (DE). Network QoS performance efficiency is measured by the ratio of performance gain to resource cost, while development efficiency is measured by the resource cost of certain level of generality.

\[
PE = \frac{QoS \text{ Performance Gain}}{Resource \text{ Cost}} \quad (1)
\]

\[
DE = \frac{Level \text{ of Generality}}{Cost \text{ for Generality}} \quad (2)
\]

A good architecture can improve the resource efficiency of the network and then enhance network performance efficiency without the cost of architecture generality efficiency, e.g., the ability to accommodate heterogeneity and adapt to a wide range of underlying communication mechanisms at diverse scenarios. An architecture built on static technologies is destined for obsolescence (Polastre et al., 2005). For example, ZigBee as an architecture cannot provide a viable solution due to “ZigBee proposes a classic layered architecture, but each layer assumes a specific instance of the surrounding layers: e.g., the routing layer assumes the IEEE 802.15.4 link and physical layers” (Polastre et al., 2005). Nevertheless, the two efficiencies are corresponding to the interest of focus for application specific performance-pursuit solution and generic widespread-pursuit solution.

Let us first consider performance and cost as two factors together. We define a new combined metric called performance efficiency (PE) as presented in equation (1). Here QoS performance is a unified quantity representing performance gain all the way through architecture evaluation and comparison. Resource costs consist of memory/CPU utilisation and energy expenditure. There needs a mechanism to weigh different parameters of interest to reveal the relationship between the coexisting elements. Most importantly, the performance and cost indicators should have threshold values assigned to each metric as essential part of evaluation algorithm. Once resource bottleneck metric has come to the threshold value, or performance metrics come to the lower bound threshold, no further performance efficiency evaluation is needed. Since QoS performance is not an absolute value which is relative to evaluator’s preference of metrics of interest and weighing indices of metrics, the measure of goodness is subjective relevant to evaluators’ intention. Furthermore, QoS performance is not a static value which is dynamic changing at spatial and temporal space, thus PE will demonstrate statistical characteristics as workload, underlying environment and system utilisation change as shown in Zakharia (2010).

Figure 3 Architecture efficiency in two aspects (see online version for colours)

Secondly, let us consider generality and cost as two factors together. We define a new combined metric called development efficiency (DE) as shown in equation (2). Here Level of Generality can be an ordinary number or a relative percentage to represent the extent to which generality is preserved in the design. Resource Cost for Generality is the extra amount of resource cost for generality purpose extra coding. Putting development efficiency (DE) in system development life cycle (SDLC) context as shown in Figure 4, architecture DE concerns beyond the QoS performance metrics.
such as throughput, delay and reliability of current implementation. Performance of the architecture in SDLC concerns more metrics that can facilitate the openness and widespread application of the architecture, which is related to architecture quality assurance attributes such as updatability, compatibility, maintainability, testability, flexibility, portability, reusability, interoperability. According to McCall model (McCall et al., 1977), these attributes are grouped into three categories in SDLC process: operation \{ updatability, reliability, and compatibility \}, transition \{ portability, interoperability, reusability \} and revision \{ maintenance, testability, flexibility \}. Among these metrics we explain some of the metrics specifically relevant to architecture development efficiency:

**Architecture portability**: the level of efforts needed to transfer a software program from one platform to another platform.

**Architecture flexibility**: the level of efforts required to modify an operational program to accommodate changing needs or a changing environment.

**Architecture interoperability**: the effort required to couple one software system to another.

**Architecture compatibility**: protocols capable of co-existing in harmony under one system for the potential response to wide application scenarios.

![Figure 4 SDLC and architecture efficiency (see online version for colours)](image)

Thirdly, let us consider the tradeoff of the two identified efficiency concepts performance efficiency (PE) and deployment efficiency (DE) in Figure 3. Through aforementioned concepts extraction, a triangle constraint three dimensional problem is reduced to a two dimensional tradeoff problem. No absolute merits are possible in tradeoff evaluation, and only relative merits can be obtained on preference bases as introduced in Analytic Hierarchy Process (Saaty, 1980; Zhu et al., 2005). The challenge here is how to quantify the cost and benefits of architecture decisions, specifically the tradeoff of two identified efficiency concepts. In regarding to practical method of obtaining architecture efficiency measure, Reference (Zakharia, 2012) has some comprehensive practice. This paper explains how different computer architectures subject to specific workloads will translate into different Architectural Efficiency profiles which represent patterns of behaviour that depend on the characteristics of both architecture and workload. We will not go further down to this topic in this paper.

In summary, in this section we present a qualitative evaluation framework at system designer’s perspective. This high level abstraction only concerns common fundamental issues in system design and evaluation. In this framework, evaluation metrics are not treated at the same level. A hierarchy of metrics is introduced to distinguish its effective scope. QoS performance, generality and cost are at the top of the hierarchy as most important factors in the evaluation process. Under QoS performance, there is second level of metrics: response time, reliability, throughput etc. which is usually main concerns of other QoS related work. However, this work mainly focus on qualitative framework aspects. We will not go further to explore experiment and measurement aspects. Instead, in next section, we will show a simple example of how our evaluation framework can provide a new way to classify and evaluate WSN architecture for benefit of system designers.

### 4 Taxonomy and evaluation of WSNs architecture from TCTM perspective

Typically, we categorise communication architecture according to layering status, namely layered architecture, cross-layered architecture and layer-less architecture. The classification method is from structure point of view, but not powerful enough to fully explore the essence of WSNs. Such a wide range of network architectures and deployment options have never been available to network designers before. How to classify and evaluate qualitatively and quantitatively to decide its suitability for specific application is tediously hard only from structure organisation. Now TCTM model provides a new way to classify and evaluate WSNs architectures according to three critical metrics, namely cost, performance and generality, or system designers can further tradeoff performance efficiency and deployment efficiency as applications preference circumstances needed. As shown in Figure 3, there are three extreme forms of architecture which emphasises one metric only:

- generality
- high performance
- low cost.

From this vein we can identify inherent merits of structured architecture (Prasad, 2008; Kawadia and Kumar, 2005) as such as:
Layered: Allowing parallel and independent development, generality best, performance and cost poor. OSI 7-layer reference model was an attempt to abstract common features to all approaches in data communications (cost high). Since the main goal of the OSI model was to allow multi-vendor computers to interact and communicate (generality and interoperability achieved), QoS performance was not thought of and thus not an issue in the design process. The stack design is highly rigid and strict. This results in a nonexistent collaboration between the different layers, presumably because no-one at that time saw any need for such a feature. In the literature, stringent layered architecture in WSNs is uncommon.

Cross-layer: Generality modest, better performance and cost when dealt with caution. Layered structure is roughly kept (generality partially maintained). The information between layers is shared to facilitate optimal configuration (performance gain). Cross-layer techniques allow application adaptation based on the underlying channel and network characteristics and network and link adaptation to application requirements (efficiency). Cross layered architecture is popular in WSNs literature. CLAMP (Madani et al., 2007) is one example cross layer architecture among others.

Layer-less: Application specific development, generality lost, possible best performance and energy cost, but with unseen problem in development process. Absolutely orthogonal to the concept of strict layered structure is the concept of Layer-less Protocol Stack. This will allow rich interactions between the building blocks of the protocols. All the protocols will be treated as a single mathematical construct that must be jointly optimised due to complex interdependencies. The utmost performance potentials can be achieved at the cost of interoperability. IDRA (De Poorter et al., 2011) is a recently proposed layer-less WSNs architecture.

Now when we review the research literature in WSNs architecture area with cost, generality and performance as three core pillars to lay our judgement, we get a very different view of the research landscape.

Performance focused architecture: majority of the early years research belong to this category. Little attention has been paid to interoperability, since it has focused on producing systems and network stacks that help in attaining research results (e.g., Dunkels et al., 2007; Buonadonna et al., 2001). Moreover, research deployments have been homogeneous in both hardware and software, providing little incentive for work towards interoperability. Focus is on the fundamental problems of specific application scenarios, leaving standardisation and interoperability to the time when the fundamental issues were addressed. Even the performance metrics (like reliability, timeliness, and lifetime) are biased based on the application requirements. There are a broad spectrum of protocols and abstractions which in essence belong to this catalogue. Vertical integration is common practice. Every piece is very efficient, but completely incompatible with almost anything else.

Cost focused architecture: Cost concerns mainly battery as well as computing resources. Communication is the far more expensive than computing. Therefore, how to process information locally to reduce communication overhead is a main concern in this area. An example of ultra low power system architecture for WSNs is introduced in Hempstead et al. (2005). The architecture replaces most of the functionality of a general purpose microcontroller with an event-driven system specifically optimised for monitoring applications. Another example is cost focused architecture is PAWiS (Mahlknecht et al., 2005). The goal of the PAWiS project is to develop efficient system architectures and the related design methodology for power aware WSNs nodes that allow for capturing inefficiencies in every aspect of the system. These aspects include all layers of the communication system, the targeted class of the application itself, the power supply and energy management, the digital processing unit and the sensor-actor interface.

Generality concerned architecture: From architecture perspective, any protocol built on static technologies is destined for obsolescence. Interoperability is essential for the commercial adoption of WSNs. However, existing sensor network architectures have been developed in isolation and thus interoperability has not been a concern at start. Early efforts on this issue are D. Culler group’s work (Polastre et al., 2005; Culler et al., 2005). The authors have presented a unifying link abstraction for WSNs. The main goal is to achieve generality and efficiency. They consider Sensor-net Protocol (SP) as a ‘narrow waist’, just like internet protocol for the internet. SP is an abstract layer present between the network layer and the link layer enabling different routing and MAC schemes to coexist. The work in Tirkawi and Fischer (2009) although did not provide a tangible architecture, they have introduced the key challenge in generality of WSNs. The authors in Ko et al. (2011) present two complete and interoperable implementations of the IPv6 protocol stack for WSNs, one for Contiki and one for TinyOS, and show that the cost of interoperability is comparable low. Their performance and overhead is on par with state-of-the-art protocol stacks custom built for the two platforms.

The very recent research (De Poorter et al., 2011; Troubleyn et al., 2008) has shown tendency that advanced architecture aims at satisfaction of cost, performance and generality in one go. De Poorter et al. (2011) presents a flexible system architecture for next generation WSNs. They introduce
several architectural techniques that can be combined to achieve

- reducing the complexity of developing new network protocols for WSNs (generality)
- supporting heterogeneous networks (generality)
- supporting advanced QoS performance requirements. (performance).

At the same time, they claim the experiment results show the overhead cost is not dramatic compared to current art of the state architecture (cost). Troubleyn et al. (2008) presents an adaptive modular QoS architecture (AMoQoS) that can handle the heterogeneous nature of future sensor networks and applications (generality). This work enables the network to adaptively change its QoS behaviour in order to continuously deliver the most optimal guarantees with respect to energy consideration (QoS performance). No solid energy and computing resource reduction mechanism is introduced in this architecture.

TCTM evaluation model concerns only common comparable key elements. These include development efficiency optimisation, resource efficiency optimisations and QoS performance optimisations. Through emphasis shift between the three optimisations, application specific requirements are satisfied, meanwhile, less emphasised elements are not totally ignored. However, above qualitative evaluation and classification of architecture into different catalogue have lost granularity. We can further quantitatively weigh each of the three metrics to reflect its importance in architecture evaluation to suit specific application domain scenarios. Combining experiment measurement results, such that the final score of (3) will reveal the application requirement and granularity. Here $W$ for weighing, $M$ for Measuring:

$$W_{\text{generality}} \times M_{\text{generality}} + W_{\text{cost}} \times M_{\text{cost}} + W_{\text{perform}} \times M_{\text{perform}}$$  \hspace{0.5cm} (3)

Or we can quantitatively weigh the two identified efficiency instead as (4) to reflect the designer’s preference over development efficiency and performance efficiency for perceived application specific design. Here $E$ is for efficiency measurement.

$$W_{\text{development}} \times E_{\text{development}} + W_{\text{perform}} \times E_{\text{perform}}$$  \hspace{0.5cm} (4)

Notice here in equations (3) and (4), $M_{\text{generality}}, M_{\text{cost}}, M_{\text{perform}}, E_{\text{development}}$ and $E_{\text{perform}}$ correspond to synthetic metric of generality measurement, cost measurement, end user QoS performance measurement, development efficiency and QoS performance efficiency respectively. How to combine multiple measurable performance metrics to synthesise abstract performance index, is not our main focus of this paper. But definitely, it is a serious work worthy to explore further. Zakharia (2010) and Kamyabpour and Hoang (2010) provide examples of effort in modelling cost and efficiency.

5 TCTM: Futuristic architecture design

From historic viewpoint, WSNs related technologies will keep evolving as past history indicated.

- Moore’s Law is making more sufficient CPU and memory chip performance available with low power requirements in a small size.
- Power source improvements in batteries, as well as passive power sources such as solar or vibration energy, are expanding application options.
- Research in Materials Science has resulted in novel sensing materials with lower energy cost and higher reliability.
- Transceivers for wireless devices are becoming smaller, less expensive, and less power hungry. Nonetheless, the enabling technologies are evolving at different paces as indicated in Paradiso and Starner (2005) of Figure 5.

Figure 5 Relevant technology evolution trend (see online version for colours)

Comparing the progress of computing with battery and wireless transceiver technologies, computing resources (CPU and memory) are becoming easily available (more powerful, cheaper, smaller), while battery and transceiver capacity improves slower. This phenomenon has big impact on futuristic architecture design and evaluation from TCTM perspective. We can change the weighing of subcomponents (CPU, Memory, and Battery) of the cost indicator to reflect the nature of the contribution of each of these subcomponents as: relaxed, constrained, or bottleneck.
Hence we can use more relaxed resources to gain more performance improvement and degree of generality while avoiding the energy hungry or bottleneck resources like transmitting power. In this context, we can foresee more complex algorithms can be handled by WSNs computing facilities in near future for specific application domain. As enabling technologies advance and commercialisation makes further progress, generality eventually will regain its importance. Architecture evaluation should follow the technical trends to reflect the dynamic nature of technology development.

6 Conclusions

WSNs performance valuation is utmost important for its future prevalence. In this paper we start to re-consider the traditional structure perspective of WSNs architecture evaluation. Our proposed evaluation framework focuses on the three critical aspects of WSNs development, from higher abstract level, to reveal the fundamentals of the evaluated architecture. This high level abstract serves as master key that nothing is redundant. And there is nothing that is not essential to every architecture evaluated. We have illustrated how to classify and evaluate WSN architecture from TCTM model. However, there needs further work on how to turn the qualitative evaluation framework into actionable quantitative performance index. How to map architectural decisions precisely to performance gains and cost, and how to quantify the generality attribute, need to be worked out as our future research. Nevertheless, as a qualitative model, TCTM is efficient. If we can precisely model the cost relating to specific attributes, like generality cost and development efficiency, it will be helpful to system designer for evaluation and comparison of alternative solutions.

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**Description**

Aims to establish an effective channel of communication between industry, government agencies, academic and research institutions and persons concerned with related problems in sensor networks. Also aims to promote and coordinate developments in the field of sensor networks.